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Thermal Insulation
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This circular letter has been prepared to assist in answering the numerous requests for information and data on the subjects of thermal insulation and insulating materials, primarily with reference to buildings.

The Bureau has just completed a series of determinations of the heat conductivities of a large number of commercial insulating materials used at ordinary or slightly elevated temperatures. A similar series was made a number of years ago, but a number of new materials have appeared on the market since that time, and the properties of some of the older materials have been slightly changed. The method of measurement together with the results of the former series of tests was described in the October 1920 number of the Journal of the American Society of Heating and Ventilating Engineers.

The heat conductivity of a material is a measure of the insulating value of that material, the lower the conductivity, the greater the insulating value. Obviously the best conductor of heat is the poorest heat insulator. The customary measure of the conductivity of a material is the amount of heat in Btu (British Thermal Units) which will flow in one hour through a layer of the material one square foot in area when the temperature difference between the surfaces of the layer is 1°F per inch of thickness.

The thermal conductivity is a property of a material itself, and does not depend upon the size or shape of a particular piece of the material in question. The insulating value of a layer of material of any thickness depends upon the thickness as well as upon the thermal conductivity of the material of which the layer is composed. In general the insulating value, i.e., the resistance to heat flow, of a flat layer of any material is equal to the thickness of the layer divided by the thermal conductivity of the material of which the layer is composed.

The same principles are involved in what is sometimes called "insulation against cold" as in "insulation against heat." The only difference is the point of view, with regard to the direction of heat flow. The insulation of a building against the outside cold is merely a question of reducing the heat flow from the inside to the outside. The insulating value of a material depends somewhat upon the temperature of the material, but this effect is small over the small temperature ranges oc-

curring in buildings. The same layer of material would be somewhat more effective as house insulation than as oven insulation.

Table 1 of this circular gives the thermal conductivities and weights per cubic foot of various materials which have been tested at the Bureau. The weights do not include the paper or other coverings confining loose materials. Table 2 is a more practical table for general use. It gives the conductances of commercial thicknesses of various materials, and in another column gives the insulating value of the commercial thicknesses. The insulating value is merely the reciprocal of the conductance, in accordance with the definition of insulating value previously stated, viz., the thickness of the material divided by its thermal conductivity. The weights per square foot given in Table 2 include the surface coverings, if any are present. In all cases the tabulated values are the average of tests on a number of samples of each material. Since materials of this general class are not very uniform, differences in conductivity amounting to one or two in the last figure have no particular significance.

The figures in both tables correspond to an average temperature of 90°F, e.g. 110°F on one surface of the insulating layer, and 70°F on the other. At lower temperatures, corresponding more nearly to actual conditions in practice, the conductivities are a few per cent lower. For practical comparative purposes, the values at 90°F are sufficiently good.

Tests were made at average temperatures higher than 90°F and the change in conductivity with temperature thus determined over a limited range, but the results of these tests have not been included in this circular since they are not particularly significant. The average increase in the conductivity of the various materials with increase of temperature was found to be about 0.18% per degree F.

Examination of Table 1 will show that the differences in the respective heat conductivities of the various light fibrous or cellular insulating materials are not very great. Of the better insulators, (K less than 0.4) one and one-half inches of the poorest material is equivalent to one inch of the best. By far the greater proportion of the materials listed fall well within these limits. In general, the lighter the material per unit total volume, the better is its insulating value per inch of thickness. Stiff fibrous insulating boards having considerable structural strength are somewhat poorer insulators than lighter and looser materials. Heavy wall boards containing plaster in one form or another are relatively poor insulators, although they are very useful building materials and are undoubtedly valuable in retarding infiltration of air through the wall.

From the point of view of insulation only, the most important question is the thickness of insulating material to be applied, rather than what material to select, provided the choice is restricted to the class of cellular or fibrous materials. No known material in a very thin layer can be expected to provide an appreciable amount of insulation. On the other hand, a relatively thick layer may not be economical, since relatively little additional gain is made over some layer of intermediate thickness. The selection of a material for a particular purpose must be governed largely by the requirements of that purpose in the way of structural strength, cost, fire hazard, etc. The real cost of an insulating material is obviously not the cost per square foot of commercial thickness, but rather the cost per unit insulating value of the commercial thickness.

If a layer of insulating material is added to a wall, the insulating value of the wall will be increased by an amount equal to the insulating value of the layer of material added. The thicker the layer, the greater will be the insulating value of the resulting wall. The percentage increase in the insulating value of the wall, however, will depend upon the original insulating value of the wall without insulation. The percentage increase in the insulating value of an actual wall containing windows will also obviously depend upon the amount of glass surface and the air leakage around windows and doors, since these factors are unaffected by the addition of insulating materia

A great many types of walls and roofs are to be found in present day dwelling house construction. The insulating value of one type or individual may be considerably different from that of another, but in an actual building, heat losses through and around windows and doors tend to level out the effect of these differences in the properties of the walls themselves to such an extent that there are no wide variations in the amounts of fuel required to heat houses of various types of the same size in the same locality, unless air leakage around windows and doors or through very poorly constructed walls is excessive.

An estimate of the probable savings in fuel resulting from insulating or weatherstripping an ordinary dwelling house is given in Table 3. The first part of the table gives the fuel saving expressed in per cent of fuel which would have been required for a similar house without insulation or weatherstripping. In the second part of the table the savings are expressed in per cent of fuel required for a house without insulation but with weatherstripped windows. The calculations were base

data on heat transfer in building construction taken principally from the "Guide", published by the American Society of Heating and Ventilating Engineers. An average insulating material (K = 0.31) is assumed, but no commercial fibrous or cellular insulating material departs far enough from this average value to make a significant difference in the approximate figures in Table 3. Whenever insulation is involved, it is assumed that the insulation is applied to both walls and roof, and that the insulation is not substituted for some other member which is present in the uninsulated construction.

The ranges in values correspond to the extremes in wall constructions usually encountered in average dwelling houses. As a general rule, ordinary walls of solid masonry are somewhat less effective in retarding heat loss than well constructed frame or hollow tile walls. A somewhat greater percentage saving in fuel is therefore obtained by insulating a solid masonry wall than by applying the same insulation to a frame or hollow tile construction. Any house representing a considerable initial investment, particularly one with solid masonry walls, should be insulated, since the cost of insulation is a small proportion of the total, and the resulting additional comfort and fuel saving is considerable.

It should be borne in mind that any calculations dependent on experimental values of air leakage around windows are subject to great uncertainty on account of the variability of the factors involved. A well built house without weather stripping may when new show less heat loss by air leakage than has been assumed in calculating the fuel savings given in Table 3. The gain resulting from weatherstripping such a house would be correspondingly less. It should also be realized that infiltration of air is not an unmixed evil since a certain amount of ventilation is necessary. In the ordinary dwelling house air leakage is relied upon to furnish part of the ventilation, and it is unwise to attempt to prevent such leakage altogether. It does not appear, however, that ordinary weatherstripping will reduce the air leakage to an excessively low value.

The calculations involving insulation are much more definite and certain than those involving air leakage. The application of insulation results in a certain absolute saving which is independent of heat loss through or around windows and doors. The per cent saving of coal, however, is still dependent upon the heat loss through the uninsulated openings.

If a layer of material is placed in the middle of a wide air space such as that between the studs in a frame wall, greater additional insulating value is obtained than if the ma-

terial is placed in contact with the sheathing, or as a plaster base, as has been assumed in the calculation for table 3. In the former case the insulating layer not only furnishes its own insulating value, but in addition divides the air space into two parts, each of which has about the same insulating value as the original air space. The insulating value of an ordinary air space more than about 1 inch in width is equivalent to about 1/4 inch of insulating material. The addition of a half-inch layer of insulation in the middle of the air space in a frame wall is therefore the equivalent of adding about a 3/4 inch layer at some other place in the wall. The process of subdivision of an air space, however, cannot be carried too far, since the resultant spaces become narrow and are not so effective as insulators. The air space formed by the use of furring strips under plaster or stucco is about as effective as a wider air space, but narrower air spaces than this are less effective.

Aside from the saving in average fuel consumption and possible increase in comfort, the insulation of a house may allow a smaller initial investment for heating plant. In the extreme case of a structural wall of low insulating value, the addition of insulation may also prevent possible condensation of moisture on the inside surfaces of the external walls. Such condensation is due to the fact that the temperature of the inside surface of a poor wall may fall below the dew point of the air in the room. Decreasing the heat transfer through the wall by the addition of insulation will increase the temperature of the inside surfaces, and thus tend to prevent condensation.

In summer, the effect of insulation is beneficial, but too much should not be expected in this respect. Increasing the total insulating value of a wall or roof will always tend to keep the building cooler during the hot part of the day, but many other factors in addition to the insulating value enter into the question in a rather complicated way. In general, thick masonry walls having large heat storing capacities are better than relatively thin insulated walls. The insulation of roofs is probably much more effective than the insulation of walls, since the former have much greater exposure to the sun.

Refrigerator or Cold Storage Insulation

It has already been remarked that there is no essential difference between insulating against heat and insulating against "cold." A refrigerator is an enclosure maintained at a relatively low temperature, and it is desirable to reduce

~~heat transfer to the inside.~~ The same principles ~~apply as in~~ the case of house insulation, but the magnitudes are generally different. As a general rule, a refrigerator should be much better insulated than a house, both to save refrigeration (ice or electricity, etc.), as well as to produce a lower temperatur on the inside.

While no extensive discussion of this variety of insulatio will be entered into here, it may be remarked that an ordinary household refrigerator should have the equivalent of not less th two inches of insulation. If ice is used as the refrigerant, a refrigerator, when operated properly, will maintain a low eno temperature for ordinary household purposes. If mechanical (ele tricity or gas) refrigeration is used directly, the temperature ordinarily be maintained lower than by the use of ice.

The question of the so-called "moisture resisting qualitie of insulating materials merits some mention at this point, since it is an important one in refrigerator or other cold storage insulation. Ordinarily it is of minor importance in house insulation. No tests have been made at the Bureau to compare mate ials on the basis of their moisture resisting qualities, since tests of this kind should be made on completed constructions rather than simply on the materials themselves.

To the best of our knowledge, no commercial insulating material is in any sense waterproof or moisture proof. If immersed in water or kept in air at 100% humidity, one material may absorb water less rapidly than another, but this fact is of minor importance. All the materials in question are permeable to water vapor, and if the insulation is colder than the outside air and is not protected on the outside, most of the water vapor which diffuses into the insulation from the outside will condense and accumulate, eventually producing a more or les saturated state and lowering the insulating value many times. In a completely saturated state there is undoubtedly very little difference between the respective thermal conductivities of various commercial materials. The only remedy for this state of affairs is adequate protection on the outside by means of airtight coatings, and when possible, vents from the insulation to the inside should be provided. The latter allow the insulation to dry out, since the inside air is colder. As a general rule applying to insulated structures, air proof the warm side and ventilate the cold side to the colder air. In no case can the insulating materials themselves be relied upon to prevent water accumulation.

Table I

THERMAL CONDUCTIVITY OF MATERIALS

D = Weight in pounds per cubic foot.
K = Thermal conductivity in Btu. per hour., square foot, and temperature gradient of 1°F per inch thickness. The lower the conductivity, the greater the insulating values.

	SOFT FLEXIBLE MATERIALS IN SHEET FORM	D	K
Dry Zero	Kapok between burlap or paper	1.0	0.24
		2.0	0.25
Cabots Quilt	Eel grass between kraft paper	3.4	0.25
		4.6	0.26
Hair Felt	Felted Cattle Hair	11.0	0.26
		13.0	0.26
Balsam Wool	Chemically treated wood fibre	2.2	0.27
Hairinsul	75% hair 25% jute	6.3	0.27
	50% hair 50% jute	6.1	0.26
Linofelt	Flax fibres between paper	4.9	0.28
Thermofelt	Jute and asbestos fibres, felted	10.0	0.37
	Hair " " " "	7.8	0.28
	LOOSE MATERIALS		
Rock Wool	Fibrous material, made from rock, Also made in sheet form, felted and confined with wire netting	6.0	0.26
		10.0	0.27
		14.0	0.28
		18.0	0.29
Glass wool	Pyrex glass, curled	4.0	0.29
		10.0	0.29
Sil-O-Cel	Powdered diatomaceous earth	10.6	0.31
Regranulated Cork	Fine particles	9.4	0.30
	About 3/16 inch particles	8.1	0.31
Thermofil	Gypsum in powdered form	26.	0.52
		34.	0.60
Sawdust	Various	12.0	0.41
	Redwood	10.9	0.42

(Table 1 continued).

		D	K
Shavings	Various, from planer	8.8	0.41
Charcoal	From maple, beech and birch, coarse	13.2	0.36
	6 mesh	15.2	0.37
	20 mesh	19.2	0.39
	SEMI-FLEXIBLE MATERIALS IN SHEET FORM		
Flaxlinum	Flax fibre	13.0	0.31
Fibrofelt	Flax and rye fibre	13.6	0.32
	SEMI-RIGID MATERIALS IN BOARD FORM		
Corkboard	No added binder; very low density	5.4	0.25
"	" " " low density	7.0	0.27
"	" " " medium "	10.6	0.30
"	" " " high "	14.0	0.34
Eureka	Corkboard with asphaltic binder	14.5	0.32
Rock Cork	Rock wool block with binder Also called "Tucork"	16.7	0.37
Lith	Board containing rock wool, flax and straw pulp, with binder	14.3	0.40
	STIFF FIBROUS MATERIALS IN SHEET FORM		
Insulite	Wood pulp	16.2	0.34
		16.9	0.34
Celotex	Sugar Cane Fibre	13.2	0.34
		14.8	0.34
	CELLULAR GYPSUM		
Insulex or Pyrocell		8	0.35
		12	0.44
		18	0.59
		24	0.77
		30	1.00
	WOODS (ACROSS GRAIN)		
Balsa		7.3	0.33
		8.8	0.38
		20	0.58

(Table 1 continued).

	D	K
Cypress	29	0.67
White Pine	32	0.78
Mahogany	34	0.90
Virginia Pine	34	0.98
Oak	38	1.02
Maple	44	1.10

MISCELLANEOUS BUILDING MATERIALS

(Data taken from various sources)

	K
Cinder concrete	2 to 3
Building Gypsum	About 3
Plaster	2 to 5
Building Brick	3 to 6
Glass	5 to 6
Limestone	4 to 9
Concrete	6 to 9
Sandstone	8 to 16
Marble	14 to 20
Granite	13 to 28

Table 2.

CONDUCTANCE AND INSULATING VALUE OF SHEET MATERIALS IN THICKNESSES AS SOLD

W = Weight in pounds per square foot
T = Thickness in inches
C = Conductance in Btu per hour, per square foot, and per degree F.
R = 1/C = Resistance or insulating value

SOFT FLEXIBLE MATERIALS

		W	T	C	R
Cabots Quilt	Single Ply	0.14	0.35	0.72	1.39
	Double Ply	0.18	0.48	0.54	1.85
	Triple Ply	0.31	0.67	0.39	2.56
Balsam Wool	1/2" house insulation; smooth paper	0.16	0.55	0.48	2.10
	1/2" refrigerator insulation, creped paper	0.24	0.66	0.41	2.47
	1" refrigerator insulation, creped paper	0.32	1.13	0.25	4.08
Hairinsul	75% hair 25% jute	0.46	0.55	0.49	2.05
	50% hair 50% jute	0.42	0.51	0.51	1.96
Carinsul	Hairfelt between asbestos paper	0.58	0.60	0.46	2.19
Salamander	Hairfelt paper, asbestos, and cheesecloth; paper between plys				
	2 Ply	0.54	0.61	0.42	2.40
	3 Ply	0.69	0.70	0.36	2.75
Thermofelt	Jute and asbestos	0.42	0.51	0.72	1.39
	Hair and "	0.42	0.63	0.45	2.22
Nycinsul	Hair felt between cheesecloth, the latter treated with magnesite solution	0.97	0.45	0.82	1.21

(Table 2 continued)

		W	T	C	R
Linofelt	1/2 inch	0.41	0.67	0.42	2.40
Resisto	Similar of Nycinsul				
	Single	0.56	0.40	0.75	1.3[illegible]
	Double	0.77	0.62	0.49	2.05
	SEMI-FLEXIBLE MATERIALS				
Flaxlinum		0.61	0.56	0.56	1.80
Fibrofelt		0.66	0.58	0.56	1.80
	STIFF FIBROUS MATERIALS				
Insulite	Wall board	0.66	0.49	0.69	1.46
	Insulation board	0.80	0.56	0.60	1.67
Celotex	Building board	0.58	0.47	0.72	1.33
	Railroad Insulation board	0.64	0.58	0.59	1.71
	PLASTER AND WALL BOARDS				
Gyplap	Gypsum between layers of heavy paper	2.23	0.50	2.6	0.38
Sheet Rock	Gypsum mixed with sawdust between layers of heavy paper	1.97	0.39	3.6	0.27

Table 3.

APPROXIMATE FUEL SAVINGS IN DWELLING HOUSES

Expressed in per cent of fuel which would have been required for similar house without insulation or weatherstripping.

	Saving
No insulation - weatherstripped	15 to 20%
Same - with double (storm) windows	25 to 30%
1/2" Insulation - not weatherstripped	20 to 30%
1/2" Insulation - weatherstripped	About 40%
1/2" Insulation - with double windows	About 50%
1" Insulation - not weather stripped	30 to 40%
1" Insulation - weather stripped	About 50%
1" Insulation - with double windows	About 60%

Expressed in per cent of fuel which would have been required for similar house without insulation but with weatherstripping.

With double windows, no insulation	10 to 15%
1/2" insulation only	25 to 35%
1/2" insulation - with double windows	40 to 45%
1" insulation only	35 to 45%
1" insulation with double windows	50 to 55%